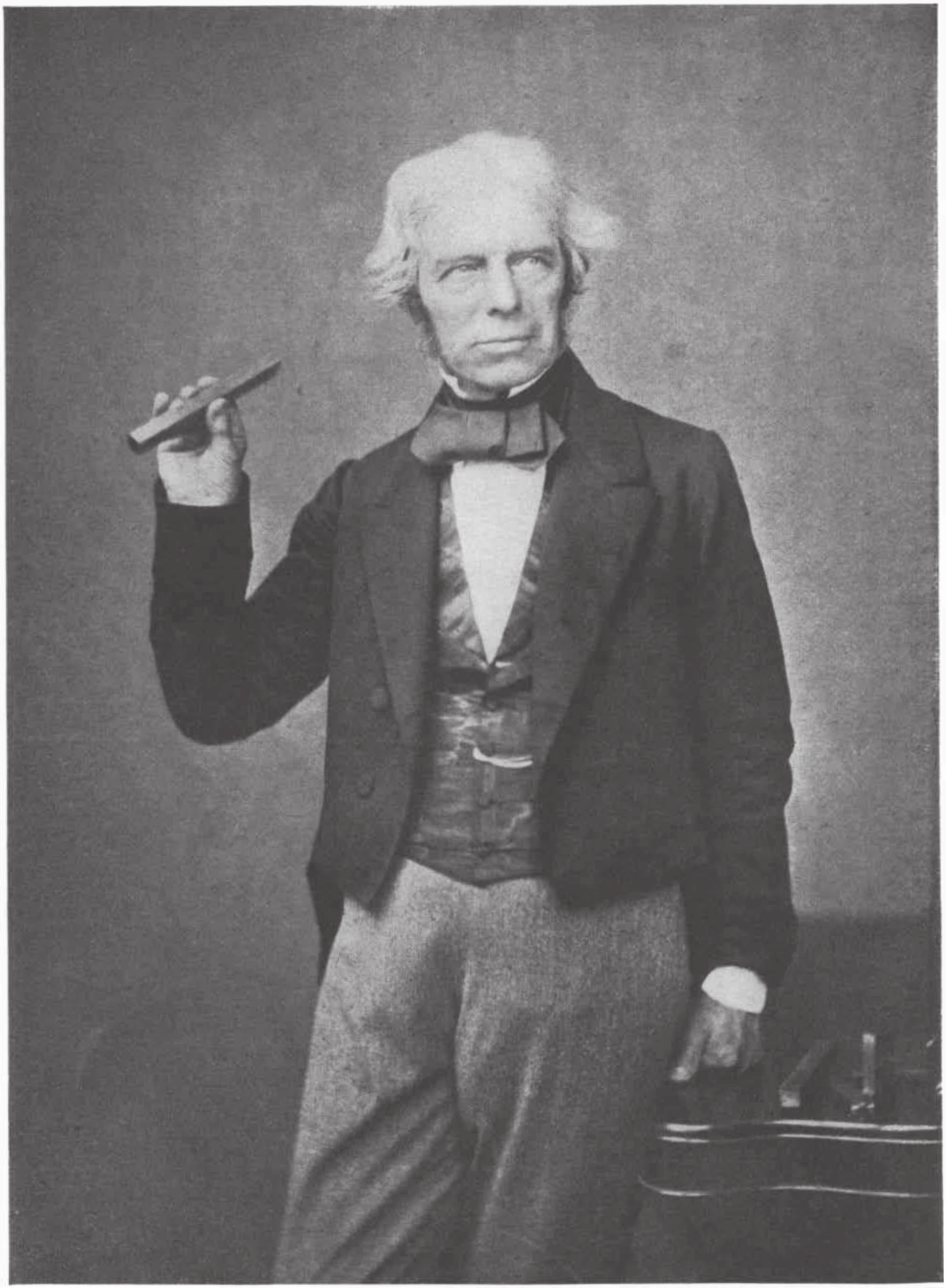


Michael Faraday (1791-1867) made advances in both chemistry and physics. In this late portrait he holds a bar of heavy glass.

Michael Faraday

His great series of discoveries in electromagnetism founded the electrical industry, but his greatest achievement was the field concept. In this he was a bold precursor of Einstein

by Herbert Kondo

Michael Faraday is celebrated as an experimenter who discovered the induction of electricity. History has more or less overlooked the fact that he was also one of the great founders of modern physics. Indeed, he can be said to be the man who started the revolution which upset the long reign of Newton and rebuilt physics on new theoretical foundations. For Faraday was the first scientist to suggest the modern idea of the field—that concept which was to become a keystone of James Clerk Maxwell's electromagnetic theory, Albert Einstein's General Theory of Relativity and the 20th century's progress toward understanding physical reality.

Not the least remarkable thing about all this is that Faraday had little mathematics and no formal schooling beyond the primary grades. To present-day physicists his achievement may well seem incredible. Actually Faraday's ignorance of mathematics contributed to his inspiration. It compelled him, when he looked for an explanation of his electrical and magnetic phenomena, to develop a simple, non-mathematical concept. His deduction of the field theory illustrates two qualities that more than made up for his lack of education: his fantastic intuition and his independence and originality of mind.

Faraday's biographers have emphasized his great intellectual energy and his obsession with his experimental researches. Fortunately for his biographers, he wrote everything down; his notes and jottings were eventually published as a seven-volume diary. Physics and chemistry were the great passion of his life; he cared little for women (although he eventually married) and less for money. He could have made a fortune from his discoveries, but he deliberately dropped every scientific project when it reached the stage of commercial value. Faraday was born in poverty and died in poverty—to him his consuming work was sufficient reward.

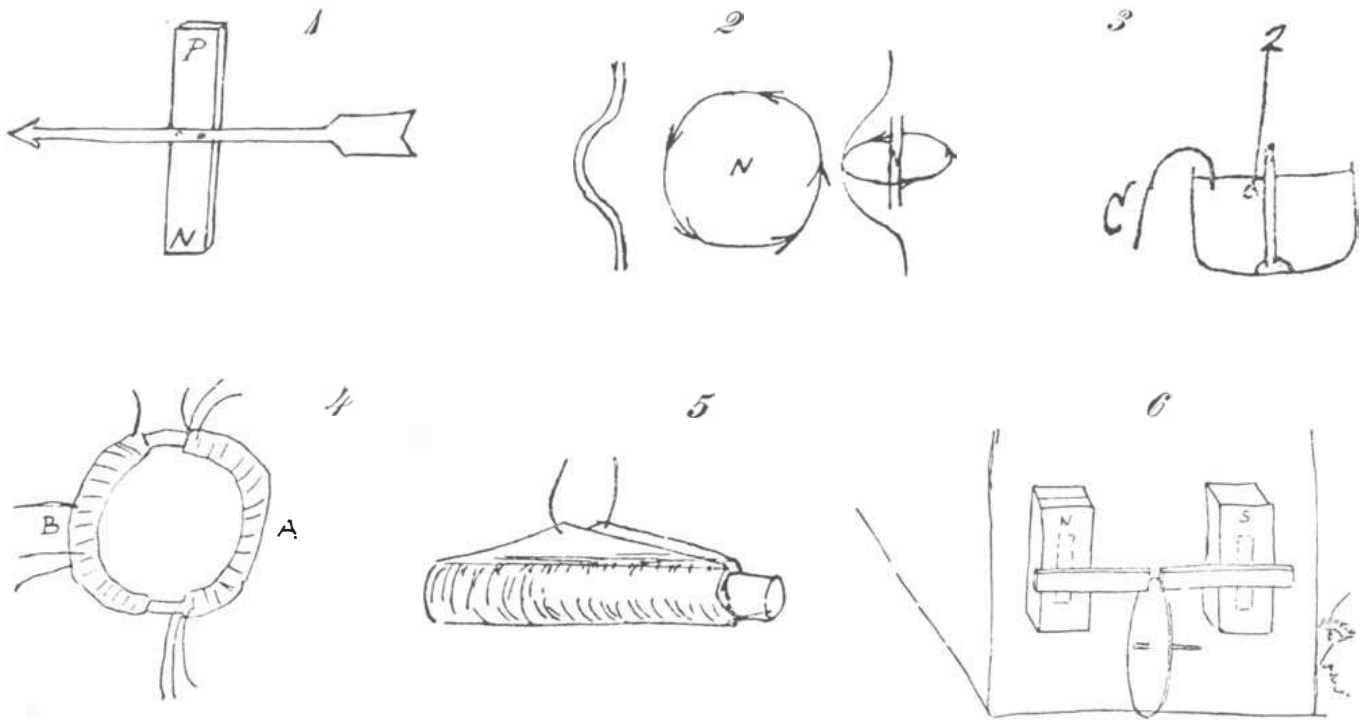
A blacksmith's son, Faraday was born near London on September 22, 1791. His family was too poor to keep him in school. "My education," he scribbled in his diary, "was of the most ordinary description, consisting of little more than the rudiments of reading, writing and arithmetic at a common day school. My hours out of school were passed at home and in the streets." At the age of 13 he took a job as errand boy in a bookshop run by a man named Riebau. A year later Riebau apprenticed him as a bookbinder for a term of seven years. Faraday developed a passionate interest in Riebau's books. "Whilst an apprentice," he wrote in his diary, "I loved to read the scientific books which were under my hands, and amongst them Marcet's *Conversations in Chemistry*, and the electrical treatises in the *Encyclopaedia Britannica*." Faraday went to hear some lectures on chemistry by the world-renowned scientist Sir Humphry Davy, and took neat and copious notes on them. He promptly applied for a job with the Royal Society and was as promptly rejected.

When Faraday's apprenticeship expired in 1812, he took a position as journeyman bookbinder with a M. de la Roche. But he was unhappy in the job and soon applied to Davy for employment, submitting his lecture notes as proof of his earnestness. Davy, a vain man, was impressed and hired Faraday as a secretary, but after a few months he dismissed the young man and advised him to go back to bookbinding. Not long afterward Davy, reconsidering, hired Faraday as his laboratory assistant.

Henceforth Faraday was to devote nearly all his working hours to research in pure science. After a two-year tour of Europe with Sir Humphry, he settled down to work in Davy's laboratory. He did experiments in chemistry, electrochemistry and metallurgy which alone would have been sufficient to establish his reputation as a scientist: he discovered benzene, produced the first "stainless steel," was the first to liquefy many gases, discovered the laws of electrolysis and the magnetic rotation of the plane of polarized light. But we are interested here in his main work—electromagnetism.

In 1820 the Danish physicist Hans Christian Oersted had announced his discovery of a relation between magnetism and electricity. He had found that a continuous current in a wire caused a deflection of a magnetic needle placed close to it. Oersted suggested that a magnetic field surrounded the wire conductor, acting in circles around the wire and perpendicular to it. In the following year the Frenchman André Marie Ampère substituted another current-carrying wire for the magnetic needle and found a magnetic force of attraction or repulsion in the two wires, depending on the direction of current flow.

Davy and Faraday, though absorbed in chemical researches, promptly became interested in the new electromagnetic discoveries. They repeated the experiments for their own satisfaction. At the same time the noted English scientist William Hyde Wollaston suggested to Davy the possibility that the magnetic field might produce rotation. Faraday interpreted this to mean the rotation of a wire about its own axis. He failed to find such a result, but he soon established for himself—whether independently or after hearing of Oersted's theory—the circular



SKETCHES FROM FARADAY'S DIARY show the progression of his electromagnetic experiments. (1) He repeats Oersted's discovery of 1820 that a magnetic needle placed near a conductor is displaced with a motion circular and perpendicular to it. (2) He bends a wire conductor into a curve, floating one end on a cork in mercury, then puts a bar magnet in the curve, causing the wire to swivel around it in the first demonstration of electromagnetic rotation. (3) In a modification of 2, he fixes the magnet upright in a bowl of mercury to allow the floating conductor to revolve completely around it—the principle of the electric motor. (4) In 1831, winding two coils of wire A and B on an iron ring and connecting A with a battery, he causes an intermittent current to flow in B, thus discovering electrical induction. (5) Plunging a magnet in and out of a hollow cylinder and coil connected to a galvanometer, he shows that induction is caused by the relative motion—the principle of the electric generator. (6) Rotating a copper disc between the opposite poles of the Royal Society's compound magnet, he induces a continuous current—the birth of the dynamo.

and perpendicular action of a magnetic field about a conductor. He therefore reasoned that if a magnetic pole were free to move, it should rotate about the conductor, and that the opposite also should be true; the conductor itself should be able to revolve about a magnetic pole.

Faraday at once undertook the famous experiments which were to lead to discovery of the basic principle of the electric motor. In his first experiment he bent a copper wire into the curved shape of a carpenter's brace; one end of the wire was stuck through a cork and floated in a basin of mercury, and the other end was connected to a battery by way of an inverted silver cup. Then he placed a bar magnet within the curved part of the wire. When current passed through the wire-mercury circuit, the curved wire swept around until it hit the fixed magnet. Faraday next modified the experiment so that the wire could revolve without obstruction around the magnet. He used a straight piece of wire with one end sticking into a cork floating in the mercury container. The passing of a current through the wire made it revolve continuously around the magnet. When the direction of the current was reversed, the wire revolved in the opposite direction. Faraday's own rough, simplified sketches of these two experiments are shown above (*drawings 2 and 3*). The straight, upright wire and the looped wire dipping into the mercury in drawing No. 3 were connected to a battery.

He now went on to perform the opposite experiment to see whether a magnet would turn around a fixed conductor. This time the bar magnet (loaded at the bottom end with platinum) floated free in the mercury and the wire was fixed. As he had expected, the magnet did revolve around the current-carrying wire.

When Faraday published the results of these experiments, he was at once charged with having used Wollaston's idea without credit. Actually Faraday had misinterpreted Wollaston's suggestion to mean rotation of a wire about its own axis; his experiments and findings were his own. In time the misunderstanding cleared up, and Faraday was nominated for membership in the Royal Society. Wollaston supported his candidacy, but Davy voted against him, possibly from jealousy. Nonetheless, he was elected in 1824.

Faraday now dropped his electromagnetic experiments and returned to chemistry. But an irrepressible idea remained on his mind. If an electric current could yield magnetism, could not a magnet produce electricity? In 1824 and again in 1825 he tried to induce current in a wire by placing a magnet near it, but these attempts failed. He did not yet appreciate the central importance of motion in the phenomena that Oersted had demonstrated. It was the motion of the electric current in the wire that produced magnetism. To obtain the reverse effect the magnet had to be moved in relation to the conductor.

In 1831 Faraday suddenly ended his chemical researches and gave himself fully to the problem that was preying on his mind. Within a single day—August 29, 1831—he found an answer that put him on the right track. His reasoning this time started from the analogy of electrostatic induction. It was known that a charged body could induce an electric charge on another body placed near it. Perhaps a current-carrying wire could induce a current in another wire placed close to it. To test this Faraday set up an astonishingly crude apparatus, illustrated here by his own sketch (*drawing No. 4 above*). Here, from his diary, is

his own account of the famous experiment:

"I have had an iron ring made (soft iron), iron round and 7/8ths of an inch thick, and ring six inches in external diameter. Wound many coils of copper round, one half of the coils being separated by twine and calico; there were three lengths of wire, each about 24 feet long, and they could be connected as one length, or used as separate lengths. By trials with a trough each was insulated from the other. Will call this side of the ring A. On the other side, but separated by an interval, was wound wire in two pieces, together amounting to about 60 feet in length, the direction being as with former coils. This side call B.

"Charged a battery of ten pairs of plates four inches square. Made the coil on B side one coil, and connected its extremities by a copper wire passing to a distance, and just over a magnetic needle (three feet from a wire ring), then connected the ends of one of the pieces on A side with battery: immediately a sensible effect on needle. It oscillated and settled at last in original position. On breaking connection of A side with battery, again a disturbance of the needle."

Faraday noted that when the circuit was closed, the needle deflected in one direction; when it was broken, the needle moved in the opposite direction. But there was no deflection while electricity was flowing in the first coil.

At last he had obtained electricity from magnetism. But he was disappointed. He had expected the current in the primary coil to induce a continuous current in the secondary coil; instead, it produced only momentary impulses at the instant when the primary circuit was closed or broken. Nonetheless, he felt intuitively that he was near success. He wrote to a friend: "I am busy just now again on electromagnetism, and I think I have got hold of a good thing, but can't say. It may be a weed instead of a fish that, after all my labor, I may at last have pulled up."

Faraday continued his experiments, and on October 17, 1831, he performed one which showed that he had caught a very big fish indeed. In this, his simplest and most famous experiment, he wound a coil, the ends of which were connected to a galvanometer, around a hollow paper cylinder (*drawing No. 5 on opposite page*). When he thrust a bar magnet quickly into the cylinder, the galvanometer needle was deflected. It moved again, but in the opposite direction, when he withdrew the magnet. Actually it made no difference whether he moved the magnet or the coil, in either case he got an induced current in the wire. It was now clear beyond doubt that what produced the current was the relative motion of the conductor and the magnetic field.

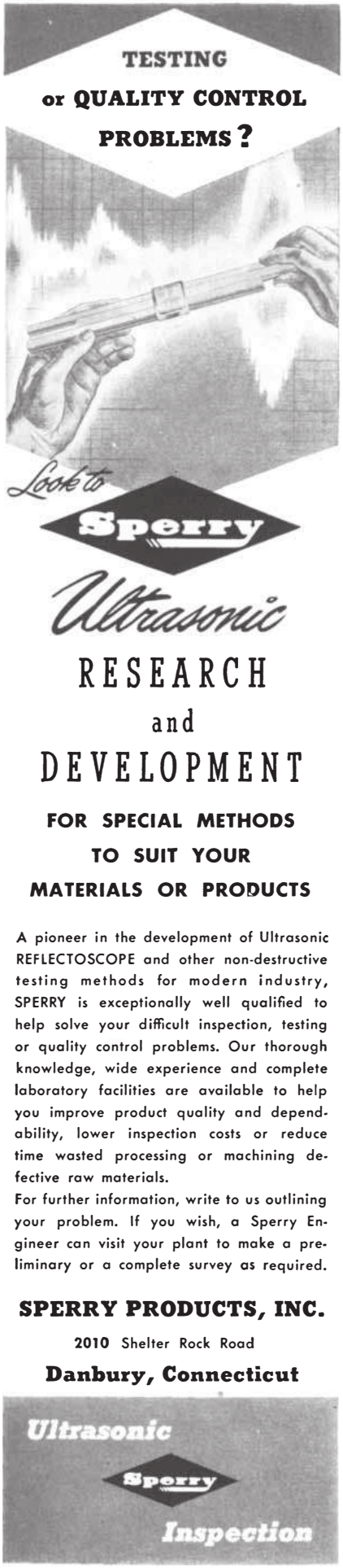
Thus Faraday discovered the basic principle of the electric generator. From this experiment it was but a step to the induction of a continuous electric current. Eleven days later Faraday achieved it with the arrangement shown in drawing No. 6 on the opposite page. Using the compound magnet of the Royal Society, he concentrated the polar strength by placing two small six-inch magnets at the ends of the large poles. Between these poles he rotated a copper disc on a brass axle. On the edge of the disc he spaced two copper contacts at different distances from the poles, connected by wires to a galvanometer. Rotating the disc, he obtained a more or less steady deflection of the needle—"more or less" because he had a hard time holding the contacts.

Faraday performed many other experiments in electromagnetic induction, but for the most part they were variations of these basic ones. His first experiment, with the iron ring, had given the world the first electric transformer; the one just described produced the first dynamo.

Faraday reported his results to the Royal Society within a month and later published these papers as the first part of his *Experimental Researches in Electricity*, rearranging the order of many of his experiments in a way that has confused historians.

As soon as the results were published, the question of priority was again raised. The U. S. physicist Joseph Henry had already discovered self-induction, and Leopoldo Nobili and Cavalière Antinori of Italy had claimed credit for the discovery of electromagnetic induction even before Faraday published his results. But they had performed their experiments after hearing of Faraday's, and Faraday was able to prove his priority.

Faraday was not satisfied with having discovered electromagnetic induction; he wanted to know why it occurred. Unable to approach the subject mathematically, he resorted to a physical model: the familiar phenomenon of the way that iron filings on a sheet of paper arrange themselves in a pattern of lines about a magnet. Why in lines? Faraday proposed the idea that the space surrounding the magnet was filled with lines of force. The magnetic force was manifest as invisible lines in a state of tension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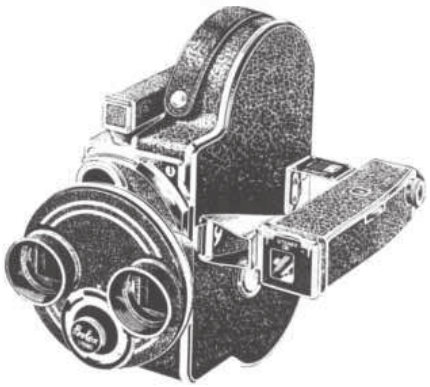

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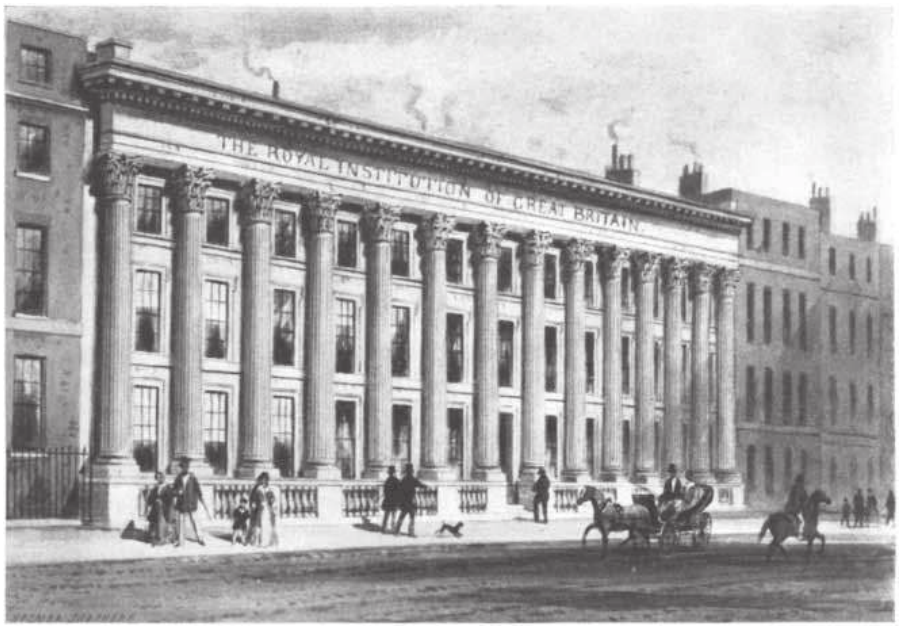
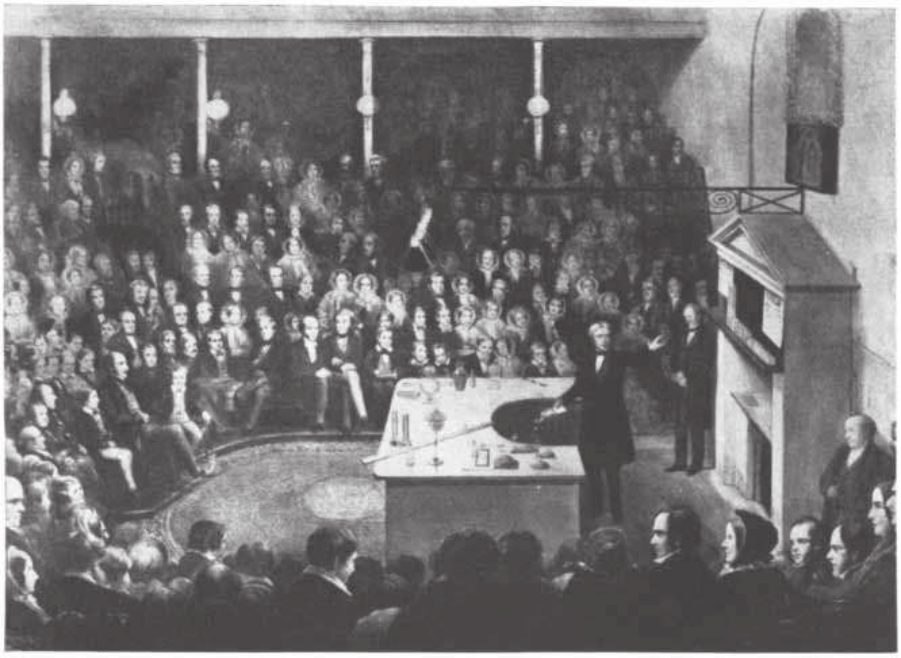


THE ROYAL INSTITUTION for diffusing knowledge was Faraday's home for half a century. It is not connected with the Royal Society, to which he was elected at age 33 in 1824.

—like stretched rubber bands—and the iron filings arranged themselves by magnetic attraction along these lines.

Faraday did not stop there. He filled *all* space with lines of force, and outlined the revolutionary concept that space was pervaded by various kinds of force: magnetic, electric, radiant, thermal and gravitational. The lines indicate everywhere both the direction and the strength of the force under consideration. For example, on a bar magnet the direction of the lines of force is from positive to negative or from north to south pole, and the number of lines of force proceeding from a magnetic pole indicates its strength at any given place. They are more dense near the magnet than they are farther away in space. Similarly the amount of electricity a body possesses is determined, according to Faraday, by the number of lines of force proceeding from it. The lines of force all terminate some place, either on another body close by, or on the walls of a room, or on the planets in space. At each terminal point there is a quantity of electricity equal in amount but opposite in charge to that on the original body.

Faraday reasoned that the lines-of-



FARADAY'S LECTURES at the Institution were attended by scientists and royalty. At the left, the Prince Consort and princes; right, Faraday's faithful assistant, Sergeant Anderson.

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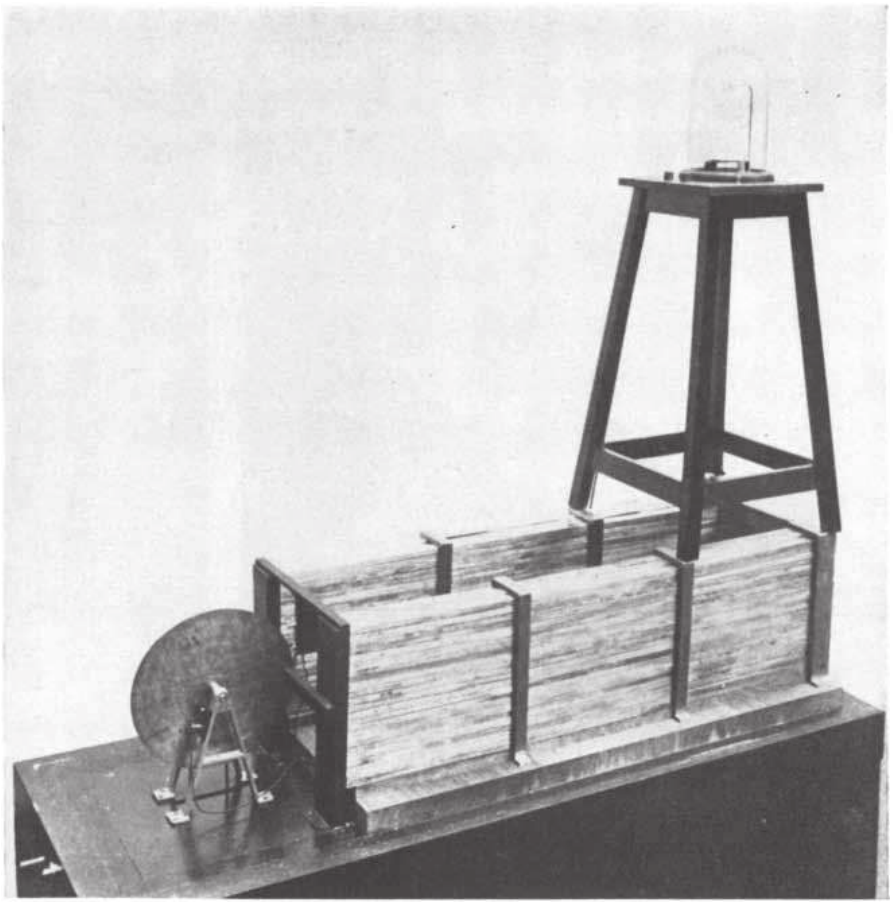

THE FIRST DYNAMO, sketched by Faraday in diagram 6 on page 92, is preserved in this model by the Royal Society in London. This apparatus founded the electric power industry.

force theory explained how a current is induced in a conductor: it is induced whenever the conductor cuts across magnetic lines of force. He discovered that the velocity of the movement was important. "If a wire move slowly," he wrote, "a feeble current is produced in it, continuing for the time of motion; if it move across the same lines quickly, a stronger current is produced for a shorter time." Strictly speaking, it is not a current which is induced but a voltage. The current merely results from this voltage.

From the idea that there are lines of force of various kinds in space, Faraday went on to suggest that these forces fill all of space. He wrote in his diary in 1846: "All I can say is, that I do not perceive in any part of space, whether (to use the common phrase) vacant or filled with matter, anything but forces and the lines in which they are exerted."

Here we have the historic origin of the field theory (see "Field Theory," by Freeman J. Dyson; SCIENTIFIC AMERICAN, April, 1953). Faraday himself never referred to his system as a "field theory" or a "field concept." In fact he held these ideas tentatively and was ready to discard them if experimental evidence could disprove them.

What is so revolutionary about the field concept? Just this. Up to Faraday physicists had concentrated on the material particle. From the particle concept they attempted to derive all phenomena. Physical processes were explained by laws of Newtonian motion and forces of mutual interaction working upon the particle. Faraday relegated the particle to the background and enthroned in its stead lines of force throughout space. To Faraday what was of critical importance was not the electric or magnetic particles but the space in which they operated. And this is the whole basis of the field concept. In field theory it is the geometric and physical condition of space itself that is fundamental.

Faraday was very clear on this point. In the *Experimental Researches* he wrote: "In this view of the magnet, the medium or space around it is as essential as the magnet itself, being a part of the true and complete magnetic system."

Here we see that Faraday actually held what is today called a dual field theory, one in which both particle and field are fundamental, but in which the field plays the basic and leading role. Thus Faraday was the forerunner of the modern relativistic revolution in physics,

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FARADAY was about 35 and doing his most important work at the time of this portrait.

and the construction of the field concept must rank as one of the greatest creations of the scientific mind.

Faraday himself did not regard the field idea as a theory distinct from the Newtonian system, but rather as one supplementing it. He did not intend to dethrone the particle concept; that came as a later consequence of his suggestion. He also started the downfall of another important concept—the idea of "action-at-a-distance." Newton assumed, and philosophers long before him had believed, that forces could act over large distances—instantaneously and without the need for any intervening medium. Only in this way, they felt, could the gravitational force between planets and stars be explained.

In the 19th century action-at-a-distance had a strong foothold in physics. But Faraday felt that this concept was unsatisfactory and that the assumptions of Newtonian mechanics were inconsistent with electrodynamic phenomena. He did not hesitate to rule out action-at-a-distance or to formulate his own concept. Force requires time for transmission, he said, and the means of conveyance are the lines of force. Wherever possible Faraday performed experiments to prove that the force in question required time. In the case of gravitational force he failed, but he did not waver from his belief that he was correct. Faraday himself did not destroy the action-at-a-distance concept; that was accomplished by Maxwell, who eliminated it from electrodynamics, and by Hendrik Lorentz, whose transformation equations banished it altogether from physics.

In May, 1846, Faraday published an interesting paper on some further speculations, entitled "Thoughts on Ray-Vibrations." In it he foreshadowed the electromagnetic theory of light. "The view which I am so bold as to put forth," he wrote, "considers . . . radiation as a high species of vibrations in the lines of force which are known to connect particles and also masses of matter together. It endeavors to dismiss the ether, but not the vibrations." Shortly thereafter Maxwell developed this "bold" view mathematically and announced his electromagnetic theory. Faraday himself had empirically established a relation between light and magnetism. In a series of brilliant experiments he had demonstrated that a magnetic field could rotate the plane of polarized light.

Faraday had a profound and prophetic belief in the underlying unity of nature and of the laws of physics. He believed that gravitational and electromagnetic forces were somehow related, and that some law or principle must govern this relationship. In 1849 he scribbled in his laboratory book: "Gravity. Surely this force must be capable of an experimental relation to electricity, magnetism, and the other forces, so as to bind it up with them in reciprocal action and equivalent effect. Consider for a moment how to set about touching this matter by facts and trial." But the numerous experiments he undertook to show such a relationship all ended in failure. In a sad yet optimistic note, he concluded: "Here end my trials for the present. The results are negative. They do not shake my strong feeling of the existence of a relation between gravity and electricity, though they give no proof that such a relation exists."

He was still at work on this problem 10 years later when he wrote his last paper. He was then in broken health, but had not given up experimenting and musing. He suffered prolonged lapses of memory, and would forgetfully repeat an experiment which he had successfully completed only a short time before. The born-to-poverty, unschooled scientist was now a life professor of the Royal Institution, living at Hampton Court. In 1867 his niece, Miss Reid, wrote to Faraday's close friend Bence Jones: "Dear uncle kept up rather better than sometimes, but oh! there was always a pain in seeing afresh how far the mind had faded away . . . This year we came with a melancholy thought of dear uncle's declining, half-paralyzed state." On August 25, 1867, Michael Faraday died peacefully in his study chair, little realizing the turmoil that was to come over whether the field or the particle is supreme.